Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
11 (2007) 1858–1872
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Connection requirements for wind farms: A survey on technical requierements and regulation

Iñigo Martinez de Alegría[a,*], Jon Andreu[a], José Luis Martín[a], Pedro Ibañez[b], José Luis Villate[b], Haritza Camblong[c]

[a]*Electronics and Telecommunication Department, Universidad del País Vasco, France*
[b]*Corporación Tecnológica TECNALIA, Energy Unit, ROBOTIKER, France*
[c]*LIPSI-ESTIA, Technopôle Izarbel, 64210 Bidart, France*

Received 31 January 2006; accepted 31 January 2006

Abstract

The increase of the wind power penetration in the electrical grids of Denmark, Germany, Spain and other countries and regions is challenging the stability of the system. The subject of this paper is to review the main problems of the connection of wind farms to the grid and how the grid codes must be adapted in order to integrate wind power generation capacity without affecting the quality and stability of the grid. This paper also summarizes the grid codes that have already been modified to incorporate high levels of wind power.

Keywords: Wind farm; Voltage control; Reactive power control; Frequency control; Fault ride-through; Grid code

Contents

*Corresponding author.
E-mail addresses: inigo@ieee.org (I.M. de Alegría), pedro@robotiker.es (P. Ibañez), haritza@estia.fr (H. Camblong).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2006.01.008

1. Introduction

Wind turbines have been treated as embedded generators, and they were not expected to contribute to the control of power system voltage or frequency. In addition, wind farms were required to disconnect from the grid under abnormal operating conditions. Until recently, wind farms connected to the grid were small-sized installations, connected at distribution voltage levels and the total amount of wind power generation capacity installed was (and still is in most countries) small in proportion to the total amount of installed generation capacity. As a result, there was previously little need for such installations to meet a defined set of grid connection technical performance requirements.

As the amount of wind power connected to the grid increases, this situation has started to change in countries such as Denmark, Germany, Spain and other regions in the world. The number of medium and large wind farms (greater than 50 MW) connected to the high voltage transmission system is likely to increase dramatically, specially with offshore wind farms. Wind power is expected to be an important contributor to power generation. Denmark has a 20% of the generation capacity supplied by wind power and expects to reach a level of 50% penetration thanks to strong grid connections with Norway, Germany and Sweden [1]. Other countries and regions (Schlesswig-Holstein in Germany, Navarra and Galicia in Spain, etc.) present similar situations.

The growth in medium and large size wind farms has reached the point in Denmark (and will reach it soon in other countries) where they have a major impact on the characteristics of the transmission system [2–4] and under low load and high wind conditions 100% of the power may be generated by wind power [5]. Denmark has been a pioneer in the connection of wind farms to the grid and is a good example of what may happen in the near future to other countries. Many of the wind farms installed in Denmark use old squirrel cage induction generator technology which has limited ability to provide voltage and frequency control. The key operational issues that have arisen in Western Denmark are described in [1]. Western Denmark has more or less reached saturation and turbines have to be temporarily shut down under certain network conditions.

Another example of a country that must already cope with these problems is India. The case of India is a good example of the problems associated with weak power grids. The penetration of wind power has reached levels high enough to affect the quality and stability of the grid [6]. Islands with high wind resources also present power quality problems. New Zealand expects a 30% share of wind power in the grid in the next 10 years [7]. Canary Islands and New Caledonia present similar situations.

Conventional power plants employ synchronous machines, which are well understood by Network Operators and Generators. Synchronous machines will assist in maintaining transient stability, good voltage control, reactive power support, frequency control and fault ride-through capabilities, thus being able to meet the connection requirements defined

by the system operators. The counterpart to synchronous machines in wind farms are mainly fixed speed asynchronous generators, doubly fed induction generators and synchronous generators with back to back converters. Their technical characteristics are very different to those of synchronous machines. The growth in wind power penetration will have a large impact on the technical and operational characteristics of the Transmission System.

The technical and operational characteristics of the power system are determined by the network, by the technical characteristics of the generation, and to a lesser extent, by the loads connected to it. Wind farm developers and network operators must work together to define a set of minimum technical performance requirements in order to accommodate significantly greater volumes of wind generation without destabilization of the grid and to ensure continuing maintenance of network security and hence security of supply while allowing a greater volume of wind farms to be connected to the system [8].

In a system with well matched loads, large load following capacity generators, high power reserve and strong interconnections with neighbour grids wind penetration can be in the range of 30–40%, without compromising the reliability of the power system. In isolated systems the percentage may be as low as 10%.

The next chapters describe the grid codes that have been modified or are in process of modification and the main problems to be solved.

2. Grid codes adapted for wind power integration

With the objective of enabling wind generation to connect to the transmission system without unnecessary restrictions and at the same time ensuring the security of supply, different transmission system operators have to adapt their grid codes. This process involves the confronted interests of four main interest groups [9]: wind farm developers, wind turbine manufactures, existing system users and utilities. On one side wind farm developers and manufactures, reluctant to accept new requirements that may increase the cost of the wind farms but at the same time interested in a clear set of requirements which will allow standardizing production, and on the other side existing system users and utilities, concerned on the safety of the system.

As a logic result of the higher penetration of wind power in both countries, Denmark and Germany [10–13] have been the first countries adapting their grid codes for wind power integration in high voltage networks. Eltra and Elkraf, the Danish System Operators, have developed specific grid codes for voltage networks under 100 kV as well in 2004 [14]. Though in many papers E.On system operator in Germany appears to be the first adapting the grid code for voltage ride through in wind farms, it was actually in Denmark where the first specific grid code for wind farms was implemented.

In the United States a new Standard published in 2004 [15] by the Federal Energy Regulatory Commission (FERC) regulates the connection of generators to the grid, but it was not specifically adapted to wind farms. The American Wind Energy Association (AWEA) filed a petition for modification of the text, in order to integrate great amounts of wind power [16]. After the modifications were accepted, requisites for connection to the grid of wind farms rated above 20 MW are similar to those in Europe [17]. Different system operators in the USA and Canada have also set their own standards based on the Danish and German grid codes [18–20].

In Spain a new grid code proposal was made public in March 2005 [21]. Holland, Sweden, Ireland and the United Kingdom have updated or are in the process of redefining their grid codes [22–31].

Other countries still demand wind turbine disconnection after grid faults [32], but most system operators are adapting their grid codes based mainly in the German and Danish grid codes. References [33,34] show in-depth studies of the differences between the grid codes of Denmark, Ireland, Scotland, Germany and Sweden.

3. Main technical Issues in wind farm connection to the grid

If the wind farms would be installed solely to maximize energy output they would have major limitations in terms of:

(a) Voltage and reactive power control.
(b) Frequency control.
(c) Fault ride-through capabilities.

These are the three main points that new grid codes must adapt for wind farm connection. The most worrying problem that wind farms must face is a voltage dip in the grid. The effects of transient faults may propagate over very large geographical areas and the disconnection of wind farms under fault conditions could pose a serious threat to network security and security of supply because a great amount of wind power could be disconnected simultaneously.

3.1. Voltage and reactive power control

In order to understand voltage control it is useful to describe a simple model of a power system. This simplified power system model has a generator at the sending end, a power line and a load at the receiving end (Fig. 1). Let E and V be the voltage at the sending and receiving end, respectively. The power line has a resistance R and a reactance X. P and Q are the transmitted active and reactive power at the receiving end.

The voltage gradient from sending end to receiving end is

$$\begin{aligned}\Delta V &= E - V = ZI = (R + jX)\left(\frac{P - jQ}{E}\right)\\ &= \frac{RP + XQ}{E} + j\frac{XP - RQ}{E} = \Delta V_p + j\,\Delta V_q \approx \Delta V_p,\end{aligned} \tag{1}$$

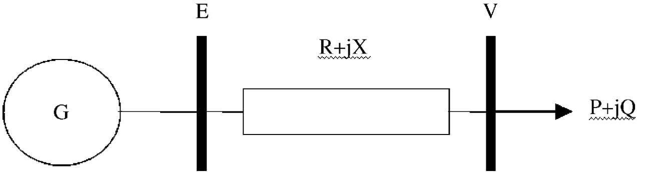

Fig. 1. Single line diagram of a simple radial power system.

where

$$\Delta V_p = \frac{RP + XQ}{E}. \tag{2}$$

In most networks $X \gg R$ and hence

$$Q \propto \Delta V. \tag{3}$$

This means that the magnitude of the voltage is controlled by the reactive power exchange, whereas the phase difference between sending and receiving end is dictated by the active power. The active and reactive power flow between the generation and the load in the power system must be balanced in order to avoid large voltage and frequency excursions.

When a fault occurs, there is a voltage drop along the circuit proportional to current and to distance from the substation. Wind farms are often located in remote locations, the distance to the substation may be very long and the connection may be radial. In this case the impedance is usually high and the voltage drop may be important. The regulator in the substation may not be able to rise the voltage at the connection of the wind farm without exceeding its voltage limits. Voltage control capability of the wind farm is very useful to keep the voltage profile along the system.

Voltage regulation and reactive power control are fundamentals in the distribution of electric energy. As we can see in expression (2), the voltage gradient across a transmission line determines the reactive power flow in the line or vice versa. Thus, for a given active power output, the conventional generator's Automatic Voltage Regulator (AVR) is used to determine its terminal voltage magnitude in order to supply (or absorb) to the transmission system the desired amount of reactive power. A mismatch between the supply and demand of reactive power results in a change in the system voltage: if the supply of lagging reactive power is less than the demand, a decrease in the system voltage results; conversely, if the supply of lagging reactive power exceeds the demand, an increase in system voltage results. There are stringent requirements on the extent to which the system voltage can be allowed to deviate from its nominal values [35] ($\pm 10\%$ for low voltage networks and $\pm 5\%$ for medium or high voltage networks).

Voltage or reactive power requirements in the grid codes are usually specified with a limiting curve such as that shown in Fig. 2. The mean value of the reactive power over several seconds should stay within the limits of the curve. When the generating unit is providing low active power the power factor may deviate from unity because it can support additional leading or lagging currents due to the reactive power demanded by the utility. When the generating unit is working under nominal conditions, the power factor must be kept close to unity or else there will be excessive currents.

Another advantage of local reactive power generation is the reduction of losses in the system. As the reactive power is locally generated and locally consumed, the current through all upstream devices and the power losses in the network are reduced.

Thus, the wind farm should have the capability to control the voltage and/or the reactive power at the connection point. This is essential in order to ensure secure operation of the system. The wind farm operator has the opportunity to gain additional payments for providing reactive power.

Several methods for voltage control in wind turbines are presented in [36,37].

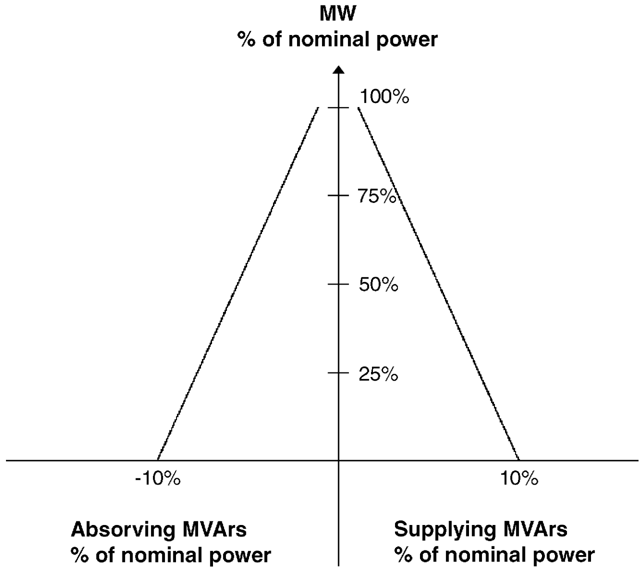

Fig. 2. Typical reactive power limiting curve.

3.2. Frequency control

The active component of electrical power output at the generator busbar is determined by the mechanical input power to the shaft of that generator. The power sources in the grid are rotating machines. The operating characteristics of interconnected machines determine how the flow of power is controlled in the system. The active power output of the generators is determined by the mechanical power input from their prime movers (steam turbines, hydro, wind, etc.).

The consequence of a mismatch between the supply (generation) and demand (load and network losses) for active power is a change in the rotational energy stored in the rotating mass of the generators, and hence, a drift in the system frequency. A surplus in generation creates a frequency increase, and a shortage in generation leads to a decrease in the frequency. The stiffness, K, of a system is defined as the ratio of the change of power to change of frequency:

$$\frac{\mathrm{d}P}{\mathrm{d}f} = K(\mathrm{MW/Hz}). \tag{4}$$

Two types of operating reserve are required: spinning reserve and supplementary reserve. Spinning reserve is the difference between the total on-line generator capacity and the total output of these generators, usually between 1.5% and 3% of peak demand. Supplementary reserve is the generation capacity that can be brought into operation in 10 min and fully available within 30 min. The operating reserve is dimensioned to cover the loss of the largest generating unit of the system. Frequency regulation ancillary service is composed by three functions:

(a) Primary frequency control limits the frequency variation caused by a sudden power unbalance in the grid, and is performed locally by the speed governor of each generating unit, within 15–30 s.

(b) Secondary frequency control or load frequency control allows restoring frequency and interchange power to their scheduled values. This is performed using units under control of an automatic central regulator within 15 min.
(c) Tertiary control consists in starting, stopping or varying the output of generating units in operation, in order to support the secondary control and to re-establish the power reserve consumed by it. This is carried out within 3–4 min (spinning reserve) or 60 min (supplementary reserve).

All the generating equipment in an electric system is designed to operate within very strict frequency margins. Grid codes specify that all generating plants should be able to operate continuously between a frequency range around the nominal frequency of the grid, usually between 49.5 and 50.5 Hz in Europe, and to operate for different periods of time when lower/higher frequencies down/up to a minimum/maximum limit, usually 47–47.5 and 52 Hz [35]. Operation outside these limits would damage the generating plants, so even very short duration deviations from the nominal frequency values would trip load shedding relays and generation capacity would be lost. The lost of generation leads to further frequency deviation and a black-out may occur.

Fig. 3 shows a typical grid code-limiting curve for frequency controlled regulation of the active power. High-frequency response can be provided from full output to a reduced output when the frequency exceeds 50 Hz and the new grid codes require that when the frequency increases above the rated value generating plants should decrease their output at a given rate. On the other hand, at nominal frequency, the wind farms would be required to limit their power output below the maximum achievable power level. By doing so, if the frequency starts to drop, the wind farm would increase the power output to the maximum achievable power, trying to sustain the frequency.

The provision of frequency response will be purchased based on the prices placed in the market. High-frequency response from wind powered generation is a service already of interest, especially at minimum demand conditions and it could become an additional source of income for wind farm owners. Low-frequency response capability would be interesting if the pay for such response would compensate the loss of generated power.

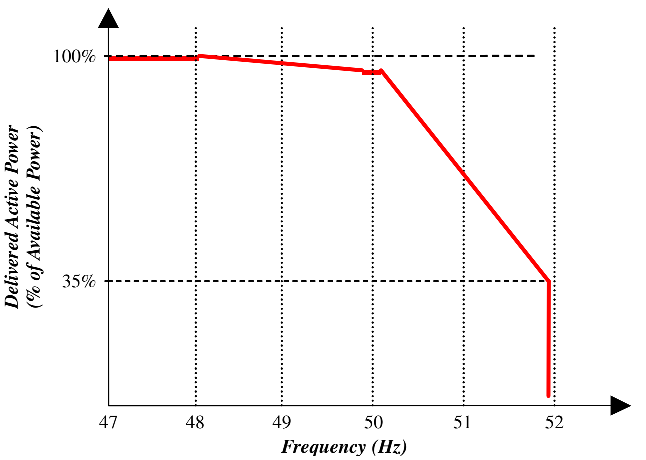

Fig. 3. Typical frequency controlled regulation of active power.

A wind farm should be capable of providing frequency response, and it would only be utilized if the system operator needs it. The active power levels of the wind farm are determined by the system operator according to the load in the system.

In order to cope with different scenarios in the grid, additional power control strategies may be necessary. Depending on the local grid code and the state of the grid, at least five additional types of power regulation may occur: Absolute Power Constraint, Delta Production Constraint, Balance Regulation, Power Gradient Constraint and System Protection.

- *Absolute power constraint*: In this type of power control (Fig. 4), the power output of the wind farm will never exceed a preset maximum, even if more power can be extracted from the wind. Below that maximum power, the wind farm power can be controlled to extract maximum power. The main reason for this requirement is that the grid operators have been obliged to pay for the produced wind power, even if there is no demand for it. When demand is low and wind power high, the operator must dump the excess wind power to neighbour grids for free, losing money in the transaction.
- *Delta production constraint*: The power production is limited below the available power by a fixed amount (MW_{delta}) as seen in Fig. 5.
  This type of power control allows the wind farm to take part in the frequency control. If there is a drop in the frequency, the wind farm is able to increase the power and help maintain the frequency. This may also help to reduce power fluctuations due to high variations in wind speed thus reducing the need for spinning reserve. For example, Koch et al. [38] describes how using a 3% of nominal power in reserve, the need for reserve capacity according to UCTE requirements can be reduced from 100% without power regulation to only a 11% reserve.
- *Balance Regulation*: In this case, the wind farm must be able to reduce/increase very rapidly its power, partly as a desired $\pm$MW and partly as a desired power gradient MW/min (Fig. 6). This is helpful in order to be able to balance the production and consumption of active power in the grid.

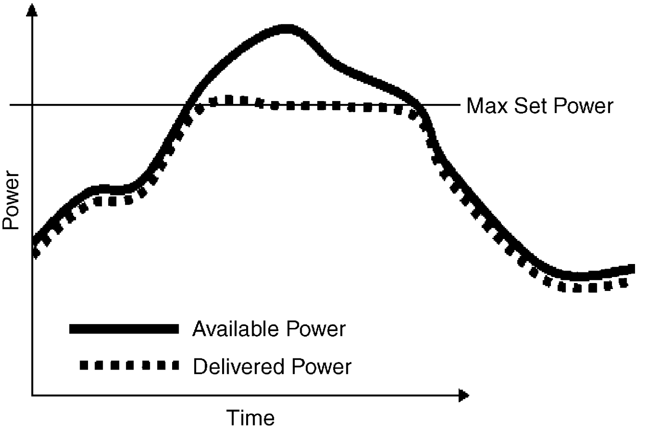

Fig. 4. Absolute power constraint.

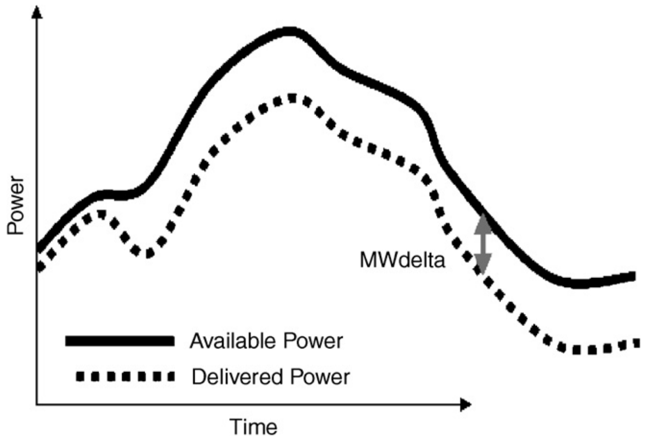

Fig. 5. Delta production constraint.

- *Power gradient constraint*: Conventional power plants cannot increase or decrease their power output at any speed. Their power increase/decrease gradient is slower than that of wind turbines. In order to keep the power balance during a conventional power plant shut-down, when the wind power fed to the grid increases to compensate for the loss of generation, a maximum wind power gradient is specified (Fig. 7).
- *System protection*: When there is overload in the grid, for instance at forced outage of a line, the grid operator will ask the wind farm to rapidly reduce its power output (in the Danish regulation a reduction from 100% to 0% power output in 30 s must be possible), and the power reduction will continue while the external protection signal is active. If the protection signal disappears, the power will be kept at the value in the instant the protection signal is disabled (Fig. 8).

3.3. Fault ride-through capability

When a short circuit fault takes place in some location in the grid, the voltage on the faulted phases will be zero. Due to the low impedance of transmission circuits a large voltage depression would be experienced across large areas on the transmission system until the fault is cleared by the opening of circuit-breakers. Extensive studies have been run to demonstrate this effect in England, Wales and Scotland [8]. The studies show how faults in the grid may propagate over very wide areas, affecting a great number of wind farms.

Some wind turbine technologies are known to be susceptible to tripping even if the voltage transiently falls to levels as high as 70%. Such plants would be affected, jeopardizing the grid stability. During voltage dips, induction generators tend to significantly increase their reactive power demand to the extent that the system voltage may be further depressed. This causes slower recovery of the voltage once the fault has been removed.

If all the wind generation in a great extension is disconnected, there is a mismatch between generated and consumed power, and the frequency will drop. If there is not enough reserve, defined by the spinning reserve of the system, a black-out may occur. If wind farms are not able to ride-through voltage dips, the Transmission System needs a

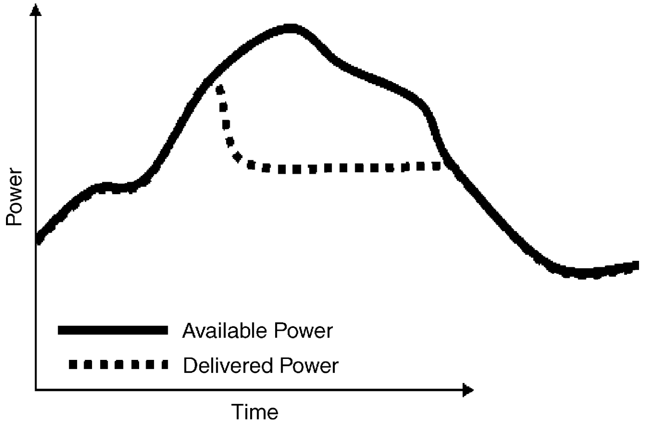

Fig. 6. Balance regulation.

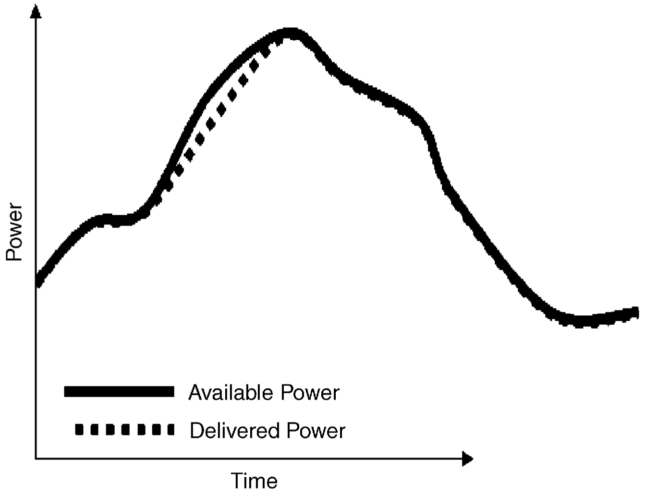

Fig. 7. Power gradient constraint.

higher spinning reserve. The spinning reserve requires that some generating operating plants operate below their optimal point, with higher losses and an increase in cost.

It is, therefore, an essential requirement that wind farms are able to remain connected to the system during a transmission system fault, where the voltage on all three phases could fall to prevent generation losses. Wind farms must also re-establish their pre-fault active and reactive power output if the wind speed remains unchanged, rapidly after clearance of the fault.

All wind turbine technologies, irrespective of type, employed in high-power wind farms, are required by the new grid codes to have a fault ride-through capability for faults on the transmission system. Usually a symmetrical 3 phase fault on the Transmission System is specified, though the proposal of the Spanish grid operator [21] and the Danish Grid Code [11] specify fault ride through for asymmetrical one and two phase faults as well. The Spanish and Irish grids are more vulnerable than other European countries, because as

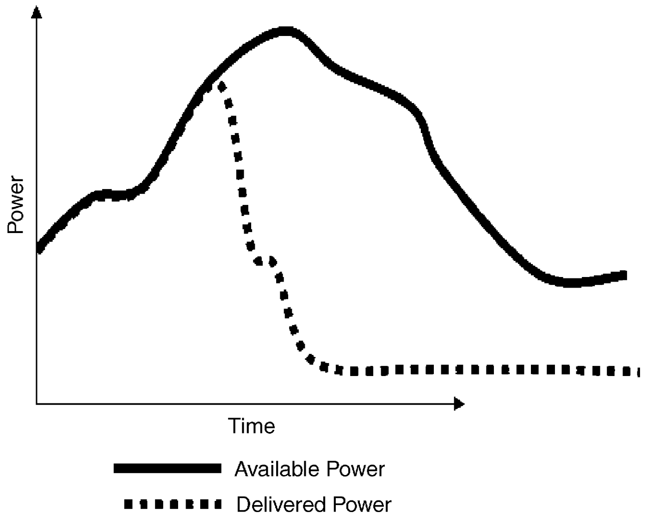

Fig. 8. System protection.

they have relatively high wind penetration, and relatively weak interconnection to neighbours, so grid faults are felt in very wide areas.

Akhmatov [5] has shown that when most of the wind power of a system is provided by small, isolated wind turbines with asynchronous generators, it is actually more convenient to disconnect the wind turbines during voltage dips, because the reactive power demand decreases, rising the voltage of the grid.

In Fig. 9 the typical requirement for fault ride-through is shown before grid code modifications and after. Wind farms must remain connected if the voltage drop, defined by the retained voltage r.m.s. value and the duration of the fault is above de curve.

The Danish Grid Code is the first official document including a simulation process to validate the wind turbines for voltage dips [11].

3.4. Wind power and spinning reserve

One of the most important and limiting factors in wind power integration in the grid is the spinning reserve needed due to the unpredictability of wind and the possible sudden loss of wind generation. Usually, a good prediction of the wind can be achieved 1–4 h in advance, but better prediction methods are still needed.

In Fig. 10 a–c, the effect of very high winds in Denmark on the 8th January of 2005 is shown (*source*: ELTRA Danish grid operator www.eltra.dk). At 11:45 most of the wind farms are operating and extracting great amounts of power. For this hour, the planned power output was 1843 MW and the real output was 1847 MW. At 16:30 the planned power output was 1782 MW. Instead of this, the wind went so high that most of the wind farms where shut down and the real power output was 126 MW. In order to avoid a collapse in the grid, a spinning reserve of 1656 MW ($1782-126=1656$ MW) or very strong connections with neighbour countries where necessary.

As wind energy fluctuations cannot be accurately predicted, a higher operating reserve must be scheduled compared to a system without wind farms. This increases the

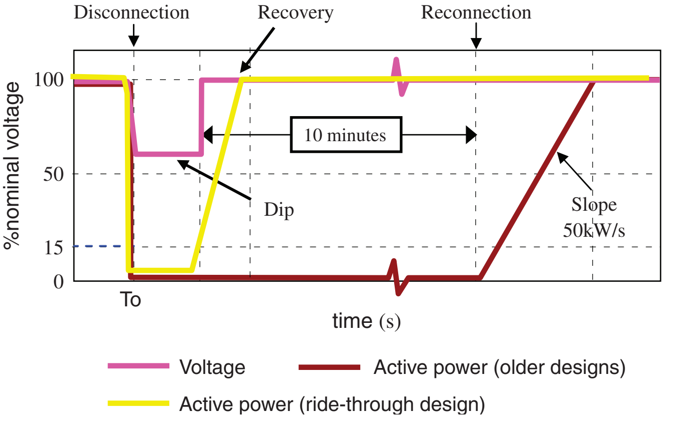

Fig. 9. Fault-through requirements.

cost of integrating wind energy into the system (i.e. more fuel consumption and maintenance).

4. Wind turbine technology

Whether wind farms will comply with the new grid codes depends on the technology of the wind turbines. There are three main types of wind turbines used nowadays: the fixed speed wind turbine with Squirrel Cage Induction Generator, the variable speed wind turbine with Doubly Fed Induction Generator and the variable speed wind turbine with Synchronous Generator.

The fixed speed Squirrel Cage Induction Generator consumes reactive power and cannot contribute to voltage control. For this reason, although static capacitor control may allow wind farms with this type of generators to provide reactive power, this type of generators are doomed to disappear from wind turbines.

The variable speed wind turbine with Doubly Fed Induction Generator can be controlled to provide frequency and voltage control with a back-to-back converter in the rotor. Control software upgrade and hardware modifications are necessary, more precisely, the converter ratings may have to be increased for frequency response [39]. This type of generator presents some difficulties to ride-through voltage dips, because voltage dip generate high voltages and currents in the rotor circuit and the power converter could be damaged. This is the most extended variable speed wind turbine technology and manufacturers already offer this type of wind turbines with fault ride-through capabilities.

The variable speed wind turbine with Synchronous Generator is connected through a back-to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips. Again, only control software upgrade and minor hardware modifications are necessary to contribute to the system stability.

Other factors such as site specific load matching (when the yearly wind profile matches the load) and a high number of wind turbines in the wind farm help smooth the operation of the grid.

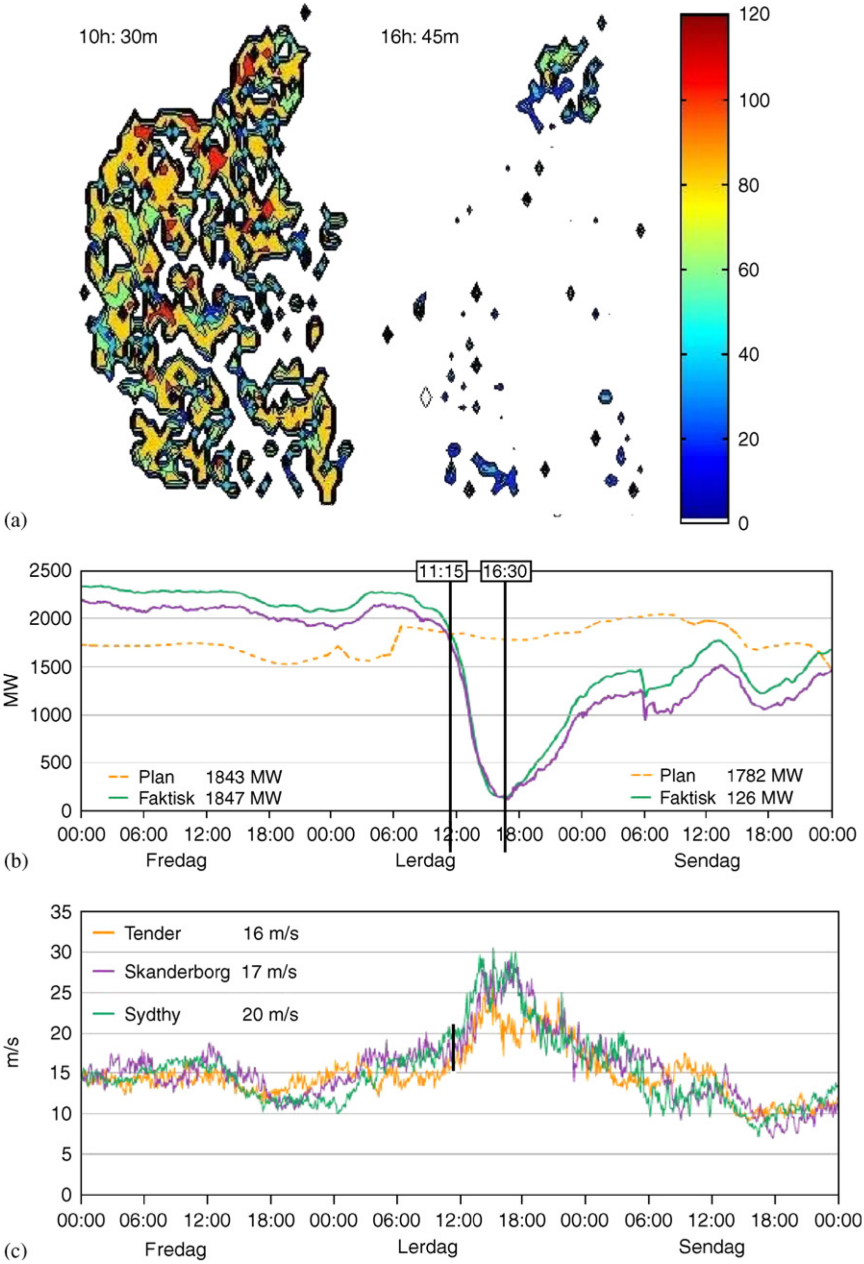

Fig. 10. (a) Available power plant production before and during hurricane (*source*: www.eltra.dk). (b) Active power production during hurricane (*source*: www.eltra.dk). (c) Wind speed during hurricane (*source*: www.eltra.dk).

5. Conclusions

A bibliographic survey of the new grid codes adapted for wind power integration has been presented. The paper also summarises the problems that are being addressed by grid codes in order to integrate large amounts of wind energy to the electric grid.

New wind farms must be able to provide voltage and reactive control, frequency control and fault ride-through capability in order to maintain the electric system stability.

In practical terms, in wind farms with variable speed doubly fed induction generators and synchronous generators, it is possible to incorporate frequency response into the turbine control system and ultimately across the wind farm with minor costs expected to be attributable to software upgrades. Wind farms with fixed speed generators will be phased out because they cannot offer voltage or frequency control.

Acknowledgment

This study was carried out with financial support from the *Ministerio de Educación y Ciencia* of Spain and FEDER within Project No. ENE 2004-07881-C03.

References

[1] Greenpeace. Wind Force 12. Available on-line: http://www.greenpeace.org.nz/pdf/wind-force-12-2003.pdf
[2] Hilger C. Wind power and impacts on power system operation—Eltra, In: Denmark. Wind power and impacts on power systems conference, Oslo, 17–18 June 2002.
[3] Masters CL. Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines. IEE Power Engineering Journal 2002;16(1):5–12.
[4] Garrad Hassan Ltd. The impacts of increased levels of wind penetration on the electricity systems of the republic of Ireland and Northern Ireland: Final Report, 11 February 2003. Available on-line: http://www.cer.ie/cerdocs/cer03024.pdf
[5] Akhmatov V. Voltage stability of large power networks with a large amount of wind power. ELTRA large-scale intregration of wind power and transmission networks for offshore wind farms seminar in Billund, Denmark 20–22 October 2003. Available on-line: http://www.eltra.dk/composite-15378.htm
[6] Sørensen P, Unnikrishnan AK, Sajan AM. Wind farms connected to weak grids in India. Wind Energy 4(3):137–49.
[7] Goodwin D, Pahalawaththa N. Going with the wind. Presentation to the NZWEA conference, Palmerston North, 16 July 2004.
[8] Causebrook A, Fox B. Modernising grid codes to accommodate diverse generation technologies, especially modern wind farms. Wind Engineering 2004;28(1):75–86.
[9] Johnson A, Tleiss N. The development of grid code requirements for new and renewable forms of generation in Great Britain. Wind Engineering 2005;29(3):201–15.
[10] Eltra. Specifications for connecting wind farms to the transmission grid, 2000. Available on-line: http://www.eltra.dk/
[11] Eltra E. Wind turbines connected to grids with voltages above 100 kV. Regulation document TF 3.2.5, 2004. Available on-line: http://www.eltra.dk/
[12] E.On. Netzanschlussregeln, Hoch und Höchstspannung, 1 August 2003. Available on-line: http://www.eon-netz.com/Ressources/downloads/enenarhseng1.pdf
[13] Verband der Netzbetriber. REA generating plants connected to the high- and extra-high voltage network. Guidelines (in addition to the grid codes) for renewable-based generating plants' connection to and parallel operation on the high- and extra-high voltage network, August 2004.
[14] Eltra E. Wind turbines connected to grids with voltages below 100 kV, 19 may 2004. Available on-line: http://www.eltra.dk/
[15] FERC. Standardization of generator interconnection agreements and procedures. Document No. RM02-1 001, 5 March 2004.

[16] American Wind Energy Association Petition for rulemaking or, in the alternative, request for clarification of order 2003-A, and request for technical conference of the American Wind Energy Association. FERC Document No RM02 -1- 001, 20 May 2004.
[17] FERC. Standardization of generator interconnection agreements and procedures—Appendix G. Order No. 661, 5 July 2005.
[18] WECC. Generator voltage dip ride through. Available on-line: http://www.wecc.biz/documents/2005/Standards/WECC_Generator_Low_Voltage_Ride_Through_Cap.pdf
[19] Alberta Electric System Operator. Wind power facility technical requirements, 21 June 2004. Available on-line: http://www.aeso.ca/transmission/6627.html
[20] Hydro Quebec. Hydro Quebec Transenergie Technical requirements for the connection of generation facilities to the Hydro-Quebec Transmission system. Supplementary requirements for wind generation, May 2003. Available on-line: http://www.hydroquebec.com/transenergie/fr/commerce/pdf/eolienne_transport_en.pdf
[21] Ministerio de Industria, Turismo y Comercio. Conjunto de procedimientos de carácter técnico e instrumental necesario para realizar la adecuada gestión técnica del Sistema Eléctrico. BOE No 51, 1 March 2005.
[22] Dte. Dutch grid code: Netcode, March 2004.
[23] Kraftnat S. Affarsverket svenska kraftnats foreskrifter om driftsakerhetsteknisk utformning av production-sanlaggningar, Stockholm, Sweden, 2002.
[24] ESB National Grid. Summary and discussion document for the review of frequency issues for wind turbine generators and wind farms, version2.7, April 2004.
[25] ESB National Grid. Summary and discussion document for the review of frequency issues for wind turbine generators and wind farms, version 2.7.
[26] ESB National Grid. Discussion document for the review of requirements for wind turbine generators under system faulty conditions, commonly referred to as fault ride through, November 2003.
[27] The England and Wales Grid Code—Revision 8, September 2002.
[28] Scottish Hydro-Electric Transmission Ltd. Consultation on technical requirements for windfarms.
[29] Scottish grid code—Version 9, June 2004.
[30] Electricity Supply Board (ESB) National Grid. Grid Code, version 1.2. 2005. Available on-line: http://www.eirgrid.com/
[31] System Operator for Northern Ireland (SONI). Grid Code. Available on-line: http://www.soni.ltd.uk/gridcode.asp.Comission for Energy Regulation. Wind Farm Transmission Grid Code Provisions, Ireland, 1 July 2004.
[32] EESTI. Technical requirements for connecting wind turbine installations to the power network. Company Standard EE 10421629 ST 7:2001 EESTI, 22 May 2001.
[33] Matevosyan J, Ackermann T, Bolik S, Soder L. Comparison of international regulations for connection of wind turbines to the network. Nordic wind power conference, 1–2 March 2004.
[34] Jauch C, Sorensen P, Bak-Jensen B. International review of grid connection requirements for wind turbines. Nordic Wind Power Conference, 1–2 March 2004.
[35] EN 50160. Characteristics of the voltage in public supply networks.
[36] Slootweg JG, de Haan SWH, Polinder H, Kling WL. Voltage control methods with grid connected wind turbines: a tutorial review. Wind Engineering 2001;25(6):353–65.
[37] Ledesma P, Usaola J. Contribution of variable-speed wind turbines to voltage control. Wind Engineering 2002;26(6):347–58.
[38] Koch F, Erlich I, Shewarega F, Bachmann U. The effect of large offshore and onshore wind farms on the frequency of a national power supply system; simulation modelled on Germany. Wind Engineering 2003;27(5):393–404.
[39] Lalor G, Mullane A, O'Malley M. Frequency control and wind turbine technologies, IEEE Transactions on Power Systems 2005;20(4):1905–13.